Photoluminescence study of long wavelength superlattice infrared detectors

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ABSTRACT

In this paper, the relation between the photoluminescence (PL) intensity and the PL peak wavelength was studied. A linear decrease of the PL intensity with increasing cut-off wavelength of long wavelength infrared CBIRDs was observed at 77 K and the trend remained unchanged in the temperature range 10 - 77 K. This relation between the PL intensity and the peak wavelength can be favorably used for comparison of the optical quality of samples with different PL peak wavelengths. A strong increase of the width of the PL spectrum in the studied temperature interval was observed, which was attributed to thermal broadening.

Keywords: photoluminescence, heterostructure, infrared, photodetector, superlattice, CBIRD, thermal broadening

1. INTRODUCTION

Antimony based type-II superlattices (SL) are considered to be one of the main candidates for next generation high performance infrared (IR) detectors. These SLs typically contain alternating thin layers of InAs and GaSb and the detection is based on type-II interband transitions between the hole energy levels located in the GaSb layers and electron energy levels in the InAs layers. The flexibility of the closely lattice-matched material system of InAs, GaSb and AlSb allows for engineering of the band gap for tailoring of the detection wavelength within the medium-wavelength IR (MWIR, 3-5 μm) region and the long-wavelength IR (LWIR, 8-14 μm) region. This material system has also enabled new barrier based detector structures [1-4] which are designed to reduce the problems of small bandgap material detectors, such as tunneling across the band gap and dark current related to Shockley-Read-Hall (SRH) processes. One of these barrier designs, which has been developed in the IR photonics group at Jet Propulsion Laboratory, is the Complementary Barrier Infrared Detector (CBIRD). It consists of an InAs/GaSb absorber sandwiched between an InAs/AlSb hole barrier and an InAs/GaSb electron barrier. This detector is expected to have favorable electron transport properties with a lightly p-doped absorber enabling high minority carrier mobility [4].

One of the crucial objectives when developing high performance superlattice detectors is to monitor the material quality of the epitaxially grown detector material. The structural quality is determined by a combination of characterization techniques, such as X-ray diffraction (XRD), surface scanning and atomic force microscopy. The material quality and the optical properties are measured using photoluminescence (PL) and absorption spectroscopy, respectively [5, 6]. In the PL measurements excess electrons and holes are generated by incident laser radiation. These charge carriers relax to the SL band edges, and then they recombine, either radiatively, emitting the excess energy as PL or non-radiatively. The carriers that recombine non-radiatively are commonly trapped by deep centers or defect levels situated in the band gap [7]. A high PL intensity consequently indicates that the material has few non-radiative recombination paths caused by defects. However, the PL intensity is also influenced by other parameters, such as the doping concentration, the sample structure and sometimes by the thickness of the material if the recombination is influenced by surface recombination [7]. It is therefore important to evaluate samples with similar structures to enable a fair comparison of the material quality of different samples.

In this study, we have compared the PL intensities from InAs/GaSb CBIRD detectors with PL peak wavelengths in the wavelength range 8.5 – 10.7 micron and we observed a linear decrease of the PL peak intensity with increasing peak wavelength. These results have been compared with the variation of the PL intensity for InAs/GaSb PL structures, grown by an external vendor. A good agreement was achieved with very similar wavelength dependencies of the PL-intensity for the two sets of samples. This relation between the PL intensity and the peak wavelength can be favorably used for comparison of the material quality of samples with different PL peak wavelengths.

1.1 Material growth

The superlattice structures studied were grown on 50 mm diameter Te-doped n-type GaSb (100) substrates in a Veeco Applied-Epi Gen III molecular beam epitaxy chamber. The structures consist of a 0.5 µm Be-doped GaSb buffer layer, followed by a complementary barrier infrared detector (CBIRD) structure [4] including a *N* period (44 Å, 21 Å)-InAs/GaSb absorber SL sandwiched between an 80-period (46 Å, 12 Å)-InAs/AlSb hole-barrier (hB) SL on the top and a 60-period (22 Å, 21 Å)-InAs/GaSb electron-barrier (eB) SL below the absorber. The hB SL, absorber SL, and eB SL are nominally doped at $n = 1\times10^{16}$ cm^{-3}, $p = 1\times10^{16}$ cm^{-3}, and $p = 1\times10^{16}$ cm^{-3}, respectively. An n-doped $InAs_{0.91}Sb_{0.09}$ layer ($n = 1\times10^{18}$ cm^{-3}) below the eB SL acts as the bottom contact layer, and the hB SL serves as the top contact layer. The energy band diagram for this structure is shown in figure 1.

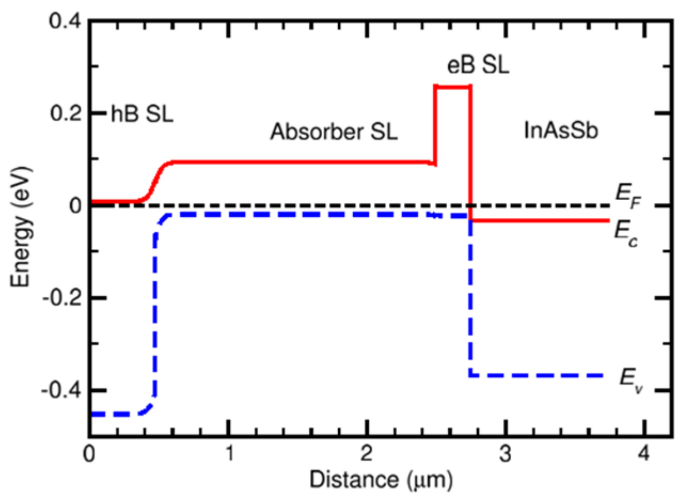

Figure 1. Energy band diagram for a 300-period CBIRD structure.

In the MBE growth, small deviations from the nominal thickness values of the absorber and differences in the strain resulted in a set of samples with cut-off wavelengths ranging from 8.5 to 10.7 micron. The number of periods (*N*) in the absorbers of the CBIRDs used in this study was 300 and 600 periods.

A second set of samples were grown by an external vendor in which the InAs/GaSb absorbers were based on the same design. These structures were grown on n-doped GaSb substrates and the structures consisted of a GaSb buffer layer, 0.5 µm AlAsSb barrier, a 150 period p-type InAs/GaSb absorber and a 100 Å GaSb top barrier.

1.2 Experiments

The characterization of the SL material consisted of two parts; PL measurements and transmission measurements, both conducted with a Thermo-Fisher Fourier transform (FT) spectrometer. The PL measurements were carried out at 11 and 77 K, respectively, operating the FT spectrometer in the step-scan mode. The samples were mounted on the cold-finger in a continuous flow cryostat and were excited by a 658 nm laser diode with an excitation power of 100 mW. The luminescence was collected by a liquid nitrogen cooled MCT detector. The transmission measurement was performed at 77 K using a DTGS detector.

2. RESULTS

1.3 Wavelength dependence of the photoluminescence intensity

CBIRDs with PL peak wavelengths varying from 8.5 to 10.7 μm were studied to evaluate the wavelength dependence of the PL intensity. A linear decrease of the PL intensity with increasing peak wavelength was observed for these CBIRDs (Fig. 2). When the PL intensity was normalized to 1 at 10 μm, the linear wavelength (WL) dependence of the PL intensity (I_{PL}) approximately equals $I_{PL}= -1\times WL+11$. A similar dependency was observed for the PL structures in which the superlattice absorber is surrounded by AlAsSb and GaSb barriers (Fig. 3) grown by an external vendor. The similarity between the two sets of samples indicate that the wavelength dependence is an inherent effect of the InAs/GaSb superlattice material and not due to the growth conditions or varying concentration of defect levels caused by the specific MBE growth chamber used. In a recent study, it was shown that the decreasing PL intensity with increasing PL wavelength is due to a decrease of the optical matrix element between the electron and hole states as the wavelength increases [8]. This wavelength dependence facilitate comparison of the PL intensities at different wavelengths, which is very valuable when optimizing the material quality of the detectors. For example a doubling of the PL intensity is expected when changing the peak wavelength from 10 to 9 μm, and the intensity would drop to half of the intensity at 10 μm if the peak wavelength is shifted to 10.5 μm.

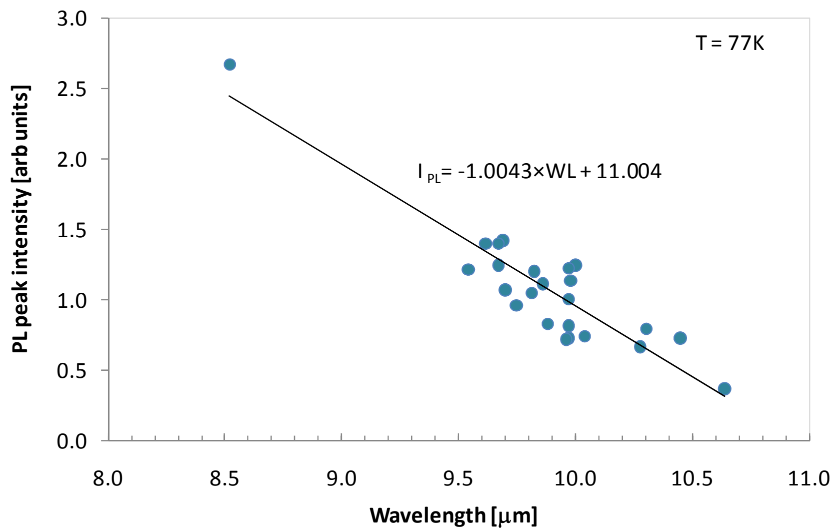

Figure 2. Wavelength (WL) dependence of the PL intensity (I_{PL}) from CBIRD absorbers. The data is collected from 23 CBIRD samples with 300 period absorbers (~1.8 μm) and 3 samples with 600 periods (~3.6 μm) in the absorber.

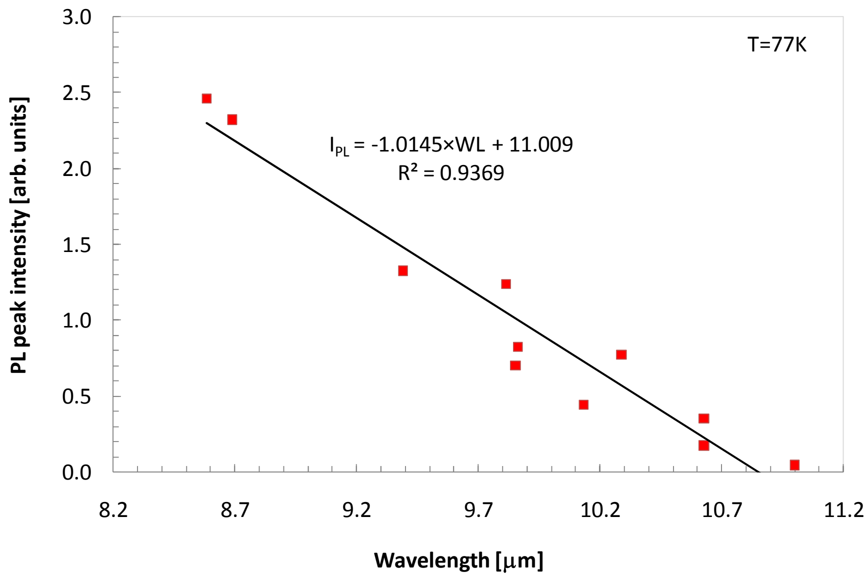

Figure 3. Wavelength (WL) dependence of the PL intensity (I_{PL}) from 11 PL structures with 150 period absorbers.

The linear dependence of the PL intensity of the CBIRDs was observed at 77K, however, wavelength dependence of the PL intensity is expected at all temperatures since the optical matrix element is temperature independent. In figure 4, the PL intensities at 11 and 77 K, respectively, are compared for four CBIRD samples, showing a maintained wavelength dependence of the PL intensity.

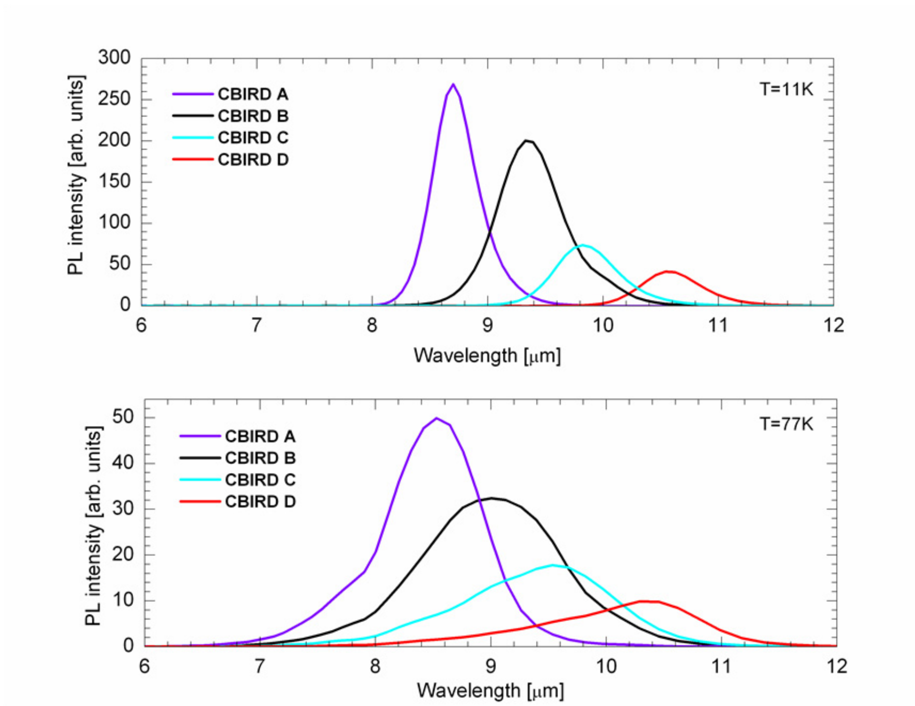

Figure 4. PL intensities of four CBIRD samples with peak wavelengths in the 8.5 – 10.5 micron region at 11 and 77 K, respectively.

When comparing the width of the PL spectra at 11 and 77 K, significant changes of the full-width-half-maxima (FWHM) are observed. On average the FWHM changes by a factor of 2-3 in this temperature interval (see Table 1). The influence of thermal broadening on the increase of the FWHM was investigated using the relation between the absorption and the radiative emission, r_{em}:

$$r_{em} \propto \alpha(h\nu)\frac{1}{e^{h\nu/kT}-1} \quad (1)$$

, where $\alpha(h\nu)$ is the absorption coefficient, h is Planck's constant, ν is the frequency, k is Boltzman's constant and T is the temperature [9]. To simulate how much thermal broadening affects the PL spectra, the absorption spectrum of CBIRD C was multiplied by the second factor in equation (1). The calculated widths of the spectra at 11 and 77 K amount 2.5 and 19.5 meV, respectively, when only the thermal broadening effects are included. At 77 K this is fairly close to the measured FWHM and a pretty good correlation was achieved between the measured and the simulated PL spectra (Fig. 5).This shows that the broadening of the PL spectra with temperature can be attributed to thermal effects. The difference between the measured and simulated values of the FWHM at 11 K is due to homogenous and inhomogeneous broadening.

Table 1. Full width half maxima (FWHM) of the PL spectra for CBIRD A-D, showing a significant increase of the FWHM when increasing the temperature from 11 to 77 K.

Sample	PL peak WL, 77 K [μm]	FWHM, 11 K [meV]	FWHM, 77 K [meV]
CBIRD A	**8.5**	**7.2**	**16**
CBIRD B	**9**	**9.3**	**20.5**
CBIRD C	**9.6**	**7.9**	**21.7**
CBIRD D	**10.4**	**6.7**	**17.4**

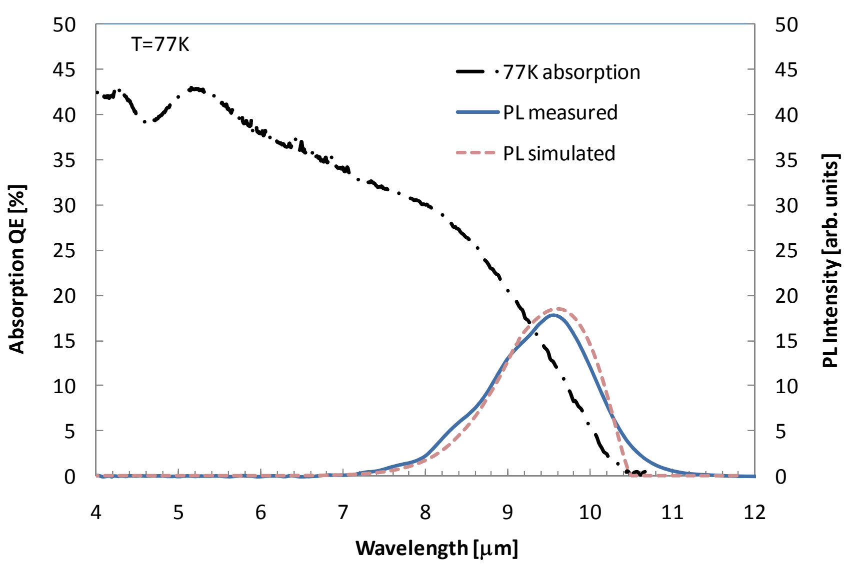

Figure 5. Emission spectrum calculated by using the measured absorption spectrum for CBIRD C multiplied by the exponential factor in equation (1). This spectrum is compared to the measured PL spectrum of CBIRD C and it can be seen that the FWHM of the two spectra are comparable.

3. SUMMARY

From studies of the PL peak intensity of InAs/GaSb CBIRD detectors as well as PL structures in the wavelength range 8.5-10.7 µm, a linear decrease of the PL intensity with increasing PL peak wavelength was observed. This dependence enables comparison of PL intensities at different wavelengths, which is very useful in detector material development. The wavelength dependence was observed at 77 K, and the trend remained valid also at 11 K. An increase of the width of the PL spectra by a factor of 2-3 was observed when comparing the widths at 11 and 77K. This increase was attributed to thermal broadening.

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